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# Quantum-dot-based deterministic photon–emitter interfaces for scalable photonic quantum technology

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**The scale-up of quantum hardware is fundamental to realize the full potential of quantum technology. Among a plethora of hardware platforms, photonics stands out: it provides a modular approach where the main challenges lie in the construction of high-quality building blocks and in the development of methods to interface the modules. The subsequent scale-up could exploit mature integrated photonics foundry technology to produce small-footprint quantum processors of immense complexity. Solid-state quantum emitters can realize a deterministic photon–emitter interface and enable key quantum photonic resources and functionalities, including on-demand single- and multi-photon-entanglement sources, as well as photon–photon nonlinear quantum gates. In this Review, we use the example of quantum dot devices to present the physics of deterministic photon–emitter interfaces, including the main photonic building blocks required to scale up, and discuss quantitative performance benchmarks. While our focus is on quantum dot devices, the presented methods also apply to other quantum-emitter platforms such as atoms, vacancy centres, molecules and superconducting qubits. We also identify applications within quantum communication and computing, presenting a route towards photonics with a genuine quantum advantage.**

Photonic quantum hardware that exploits the benefits of advanced photonic integrated circuit (PIC) technology is rapidly being developed. Quantum photonics is therefore a front-runner in quantum technology, where real-world applications emerge early. Photonics is indispensable in quantum communication as light pulses carry quantum information through optical networks. Figure 1 illustrates the concepts covered here. Our point of departure is the availability of efficient photon–emitter interfaces that provide deterministic and fully quantum coherent light–matter interactions (Fig. 1a) as implemented with a quantum dot (QD) in a nanophotonic waveguide. More generally, a single quantum emitter, such as an atom, ion or solid-state emitter, may constitute the fundamental quantum interface between light and matter, coupling a single excitation of light (the photon) to a single atomic excitation. The coupling is usually weak and any incoherent dephasing processes may deteriorate the inherent quantum properties. Both limitations have been overcome by using quantum emitters in photonic nanostructures after careful shielding of external noise (Fig. 2). Different implementations have been researched at optical frequencies, including QDs, atoms, vacancy centres or molecules[1], and the underlying physics also applies to superconducting qubits[2]. In this Review, we will focus on semiconductor QDs in nanophotonic cavities and waveguides[3–6] when considering specific figures of merit and benchmarks, which are required for predicting the scalability towards real applications. However, the proposed applications are of general importance and not restricted to the QD platform. Subsequently, PIC technology allows scaling up by processing many photonic qubits or synthesizing advanced photonic resources (Fig. 1b). PIC-based quantum processors could realize applications (Fig. 1c) and we will outline specific architectures tailored to QD single-photon hardware within quantum communication and computing. Deterministic photon sources based on photon–emitter interfaces may be considered a new tool in the quantum photonics toolbox that complements heralded probabilistic sources[7], and offers an alternative and resource-efficient route to scaling up.

## Deterministic and quantum coherent photon–emitter interfaces

A quantum emitter (a QD for example) in a single-mode waveguide or nanocavity is a prototypical deterministic photon–emitter interface, (Fig. 2). Coupling to a single mode can be Purcell enhanced, whereas coupling to unwanted leaky modes is suppressed; this is quantified by the $\beta$ factor, which routinely reaches near unity in nanophotonic devices[8]. For quantum applications, all decoherence processes must also be suppressed. The device is operated as an on-demand source of single photons by resonantly exciting the QD that subsequently emits photons into the waveguide. An important figure of merit is the degree of indistinguishability of subsequently emitted photons, and indistinguishability >95% for QDs was reported over extended timescales to produce >100 indistinguishable photons[5,6]. In another configuration, resonant photons are launched into the waveguide and the QD serves as a giant nonlinearity (Fig. 2b).

Realizing highly coherent emitters has been an ongoing challenge for solid-state systems and requires identifying and combatting all sources of noise. For QD excitations, the relevant decoherence processes are sketched in Fig. 2. They include phonon broadening, charge noise from electric charges near the QD and spin noise from coupling to the nuclear spins of the atoms making up the QD. Remarkably, charge noise can be suppressed in epitaxially grown and electrically contacted samples, and spin noise only leads to minor broadening[9]. Consequently, Fourier-transform-limited (that is, the spectral linewidth is the inverse of the radiative lifetime) QD emission has been demonstrated[10], which was subsequently realized in high-$\beta$-factor nanophotonic waveguides[11]. In this manner, a coherent and deterministic photon–emitter interface was constructed.

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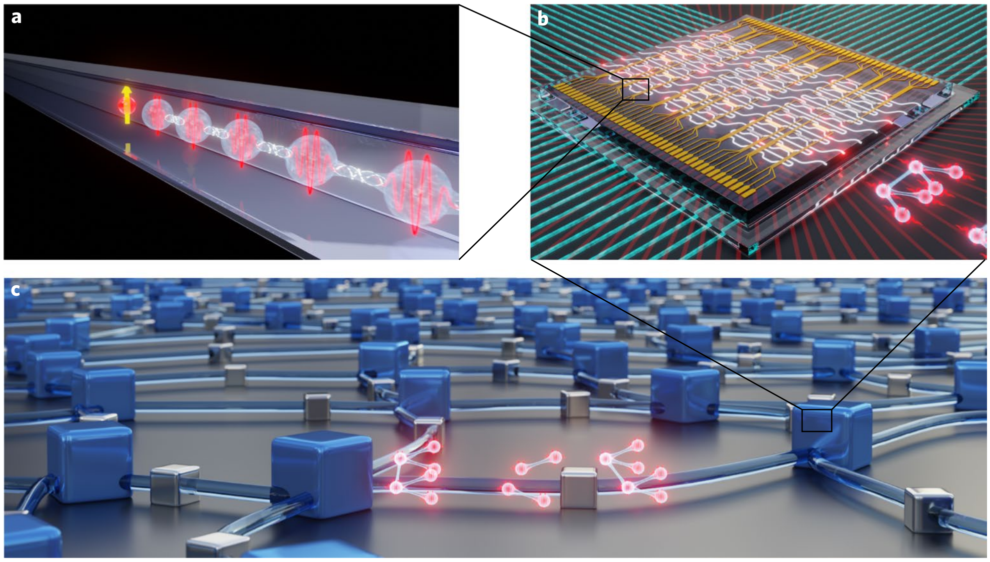


**Fig. 1 | Scalable and modular quantum photonic technology based on deterministic single-photon quantum hardware. a**, Illustration of a deterministic photon–emitter interface. **b**, Illustration of a PIC configured for synthesizing multi-photon entangled states. **c**, Illustration of advanced photonic quantum networks in which communication between network links is facilitated by multi-photon entangled pulses.

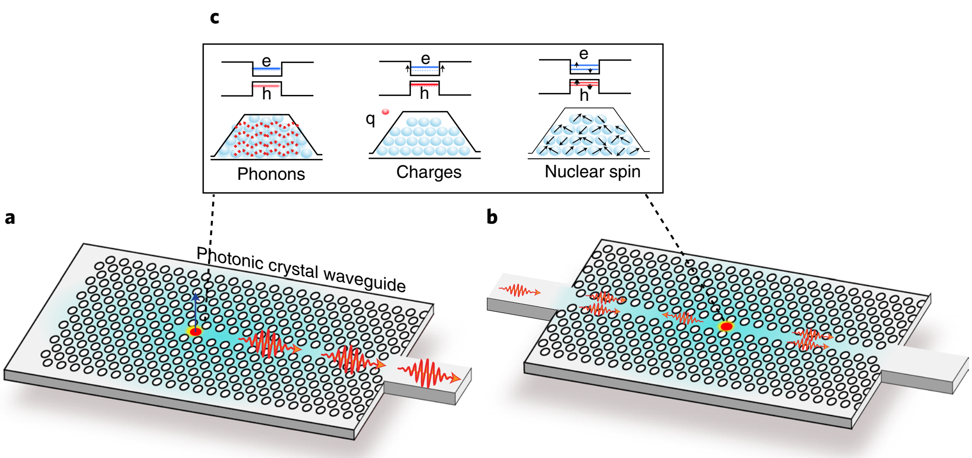



**Fig. 2 | Deterministic photon–emitter interface with QD in a planar nanophotonic waveguide.** The concepts shown here are general and also apply to other types of emitter and cavity/waveguide implementations. **a**,**b**, The devices can be operated either as a single-photon or entanglement source (**a**) or a giant single-photon nonlinearity (**b**). **c**, The relevant deteriorating decoherence processes affecting the electron–hole (e–h) pairs in QDs leading to linewidth broadening are shown, including coupling to phonons, charges *q* and a fluctuating nuclear spin bath that also decouples the electronic spin.

For high-fidelity quantum operation in advanced quantum applications, even minor decoherence must be accounted for. Phonon scattering remains the fundamental decoherence mechanism that contributes even at cryogenic temperatures, limiting the reported indistinguishability to less than 99%. An experimentally feasible strategy for indistinguishability >99% has been proposed: implementing phonon damping by clamping the nanostructures[12]. Alternatively, strong Purcell enhancement could increase the emission rate beyond the decoherence rate[13]. It was shown that QD single-photon sources suffice for realizing quantum advantage in a boson sampling quantum-simulation algorithm requiring about 50 high-quality photons[5] (Box 1). Further experiments will probably show that such a source emits thousands, if not millions, of highly indistinguishable photons since the photon emission is much faster (typically 100 ps) than slow, residual drift processes (typically acting on millisecond timescales). It will be exciting to see whether this massive photonic quantum resource delivered by just a single QD can be a key enabler in advanced quantum-information processing. This is intimately connected to how efficiently the generated string of photons can be coupled, routed and processed, which are topics covered in the next section.

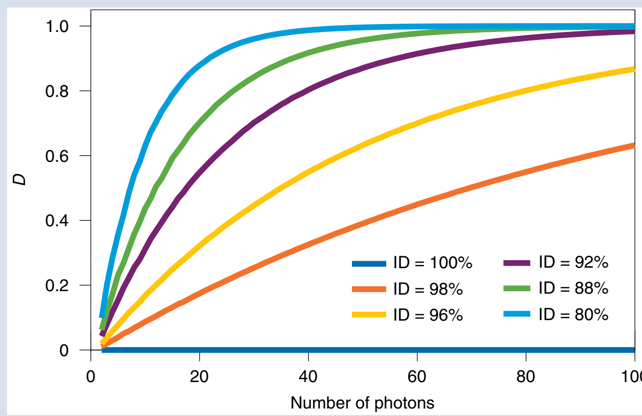
Electrically contacted QDs allow different exciton states to be addressed. Loading a single electron or hole introduces a twofold metastable ground state of spin up/down relative to an external magnetic field. The spin coherence is determined by the coupling to the nuclear spin bath, as quantified by the spin dephasing time ($T_2^*$), which is nanoseconds for electrons but reaches hundreds of nanoseconds for holes[14]. Since the nuclear dynamics is slow, spin-refocusing methods allow part of the decoherence to be reversed. The spin coherence time ($T_2$), which can reach microseconds[15], is therefore of relevance when spin-echo control sequences are implemented. Importantly, since emission is fast, a QD can emit

**Box 1 | Quantum hardware enabling quantum advantage**

What are the performance requirements of quantum hardware for carrying out tasks that are impossible classically? This question obviously has no simple answer since it depends on the specific application targeted among the multitude of applications of quantum technology. Nonetheless, this question is essential for researchers developing quantum hardware, and clear benchmarks will guide future work. Despite the diversity of applications, it is often the same physical parameters that are relevant as transformative quantum applications rely on similar physical principles, such as quantum superpositions or multi-particle entanglement. Our Review discusses these essential physical parameters for photonic qubits generated by QD sources.

Quantitative benchmarking requires focusing in on the application. For quantum simulations/computing, a benchmark referred to as quantum advantage was formulated[117]; it signifies the threshold at which the accessible hardware can implement a quantum algorithm that cannot be computed on even the world's largest supercomputer[118]. The term 'quantum supremacy' is also common in the literature; however, as has been discussed in a commentary[117], the term quantum advantage captures the importance of this technical quantum hardware achievement while avoiding associations with the historical meaning of the term supremacy. Quantum advantage was realized with superconducting qubits in 2019 by Google[119]. The boson sampling algorithm[120] can be realized as linear interference of highly indistinguishable single photons and sampling from the photon distribution. About 50 high-quality photons is sufficient to reach quantum advantage, although minor variations in the exact number could occur as optimized classical algorithms are developed. The figure in Box 1 quantifies the quality of the photons required for boson sampling. So far, 20-photon boson sampling with a QD source has been performed[62], and it has been shown that improved QD sources permit scaling up into the regime of quantum advantage, requiring a fibre-coupled source with >78% efficiency[5]. An explicit photonic quantum advantage demonstration was reported[121], albeit in this case realizing Gaussian boson sampling with squeezed multi-photon states, rather than single-photon sources. Importantly, this set-up could be generalized to control single photons from the optimized QD sources for an explicit quantum advantage demonstration of photonic qubit technology.

What are the next steps beyond quantum advantage demonstrations? This is another essential question. Indeed, current quantum advantage simulators are not solving practical problems and to justify the huge experimental efforts, they should constitute stepping stones towards addressing pertinent problems. This Review highlights opportunities identified for quantum photonics based on deterministic photon–emitter interfaces, including the route towards realizing them. The concept of quantum advantage, as discussed above, can also be formulated in a broader context than for quantum simulations alone. In the spirit of this, any protocol exploiting inherent quantum effects to realize applications not possible with classical resources could be referred to as quantum advantage. This entails applications such as device-independent quantum key distribution (QKD), quantum repeaters and certain quantum sensing protocols, to mention a few examples. The breakdown of these protocols in actual hardware architectures, including a thorough benchmarking of hardware requirements, constitutes important guidelines for quantum hardware development.




**Photon quality requirements for scaling up boson sampling.** The variational trace distance ($D$) (ref. [116]) with increasing number of photons in a boson sampler is shown. Here, $D$ quantifies the dissimilarity between a real boson sampler with partly indistinguishable photons (ID) and a boson sampler with perfect photons (ID = 100%). $D = 1$ is the computationally easy case of distinguishable photons. For partly indistinguishable photons, the computational hardness must be explicitly evaluated. ID ≥ 96% has been realized with QDs over long photon strings, which suffices for computationally hard boson sampling with ~50 photons. Figure adapted with permission from ref. [5], AAAS.

many photons within the spin coherence time, which is essential for the scalability of advanced multi-photon entanglement sources.

Multi-particle excitations provide further opportunities. Biexciton states consist of two electrons/holes in the QD and recombine through a cascaded two-photon process, generating polarization-entangled photons on-demand[16,17]. Coupling multiple QDs may be realized via coherent electronic tunnel coupling[18] or by optical dipole–dipole interaction, possibly engineered by the photonic nanostructure[19]. QD inhomogeneities introduced during growth remain a major challenge for scaling up from few-QD experiments to many QDs. Notably, most of the applications considered here require only a few QDs (and sometimes even just one). The availability of near-transform-limited QD emitters combined with spectral tuning and spatial positioning techniques provides the required tools for advancing multiple QD experiments. Nonetheless, overcoming spatial and spectral inhomogeneities at the growth and fabrication stages would constitute a major breakthrough, and new selective-area growth methods may provide a pathway to realizing the required atomic-scale control[20].

## Photonic building blocks

The application of photon–emitter interfaces in quantum technology requires interfacing with additional functionalities. Quantum photonics is favourable as it involves a modular approach in which high-quality building blocks are combined to form a complex architecture. Furthermore, the hardware can readily be realized using advanced nanofabrication equipment developed for integrated optics. Integrated photonics offers high functional stability, high mass productivity and a high level of integration[21]. Importantly, quantum photonics applications are compatible with classical PIC hardware[22], yet the performance requirements of quantum technology are pushing current boundaries, particularly towards ultra-low-loss operation. These improvements would lead to considerable spillover of technology into the area of classical 'green

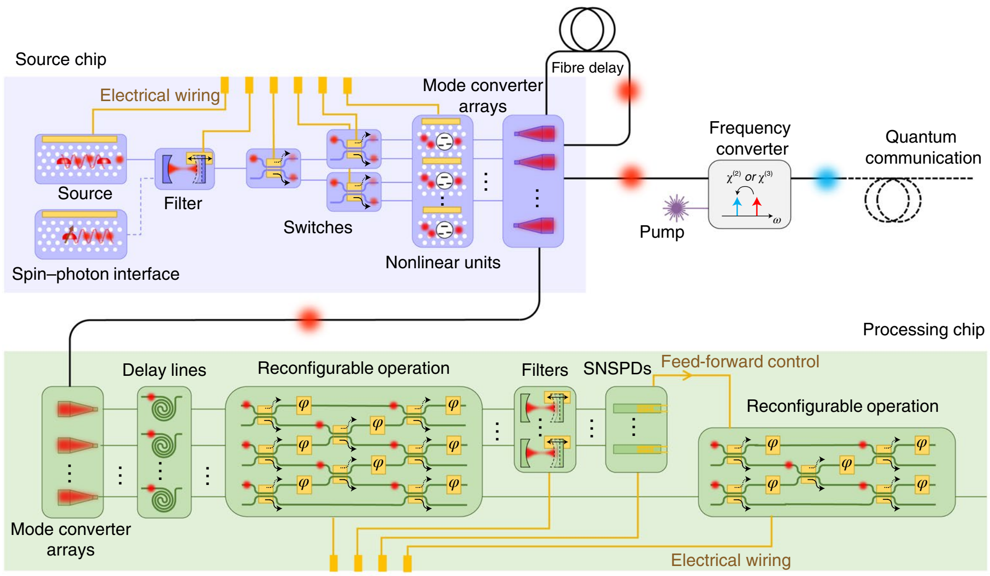



**Fig. 3 | Illustration of basic functionalities required to construct a general-purpose quantum processor based on deterministic photon–emitter interfaces.** Source chips comprise QD photon sources (single-photon sources and spin-based entanglement sources) together with spectral filters, photon routers and nonlinear units. The prepared photonic resource is subsequently coupled off-chip with efficient mode converters for various applications either in quantum communication (fibre link) or quantum computing (processing chip). Optionally variable fibre delays and optical second- or third-order ($\chi^2$ or $\chi^3$) nonlinearity-based frequency ($\omega$) conversion units are implemented. The source chip contains mode converters, on-chip optical delays, reconfigurable circuits (beam splitters and tunable phase shifters $\varphi$) to implement unitary optical transitions, filters and detectors. Feed-forward from detection using single-photon detectors (SNSPDs) is also required. The various photonic modules are discussed in the text.

IT'[23], where the rapidly growing energy consumption of the internet is a concern[24]. Quantum applications require low-loss performance due to the ubiquitous no-cloning theorem[25] stating that quantum information cannot be amplified without noise penalties. As a consequence, the scalability of quantum photonics is intimately linked to the loss performance of all involved components. Figure 3 outlines a vision for a general-purpose photonic quantum processor comprising photon sources, couplers, switches, converters, detectors and so on. We consider hybrid configurations consisting of a source chip and a processing chip[26–28] as a flexible approach well suited to current technology. The full integration of photonic quantum processors can be envisioned, for example via the heterogeneous integration of different material platforms[29].

The source chip is based on a direct bandgap semiconductor, such as GaAs, hosting high-quality QDs for photon generation and nonlinear interactions. Other source-chip functionalities include filters to remove residual light from optical control pulses and switches to demultiplex the photons. High-efficiency mode converters couple photons out of the source chip and into the processing chip. Between the two chips, optional frequency conversion modules could be implemented to compensate for variations between different QDs or to reach the telecom band, as required for quantum communication, for example. Furthermore, optical fibre delays could be inserted to control the timing of the photon stream.

The processing chip carries out the actual quantum operation on the resource produced by the source chip. This generally requires a reconfigurable PIC to interfere the photons and low-loss optical delay lines, filters and integrated single-photon detectors. Fast feed-forward from the detectors to the reconfigurable circuit is essential in many advanced applications[30]. The detectors would preferably be integrated into the processing chip, for example superconducting nanowire single-photon detectors (SNSPDs)[31]. Figure 3 illustrates the building blocks for general-purpose photonic quantum-information processing. For specific applications, an actual chip design would be laid out. For the processing tasks, explicit photon–photon nonlinear interaction may be a major asset, and extended hybrid configurations can be envisioned involving more than two chips or active routing back and forth between the source and processing chips. We briefly outline the operational principles and specifications of the various building blocks of the proposed architectures. We will not attempt to exhaustively cover the vast array of developments in integrated photonics, but instead point to specific hardware that is compatible with QD photon–emitter interfaces.

**Mode converters.** Routing photons efficiently in and out of photonic chips is required in hybrid architectures. The coupling efficiency from the chip and into a single-mode fibre is a key figure of merit, as is the chip-to-chip efficiency. Different approaches have been researched: end-fire coupling allows wide bandwidth, and 86% efficient coupling has been realized[32]. Another approach exploited vertical coupling from apodized surface gratings and a substrate metal mirror to reach 86% efficiency[33]. Finally, evanescent coupling of waveguides to tapered fibres has realized a 95% transfer efficiency[34], although it remains challenging to scale up to many fibres due to the demanding alignment requirements.

**Photonic switches.** Switches are key components in quantum photonics to route single photons into different spatial modes, for example, constituting single-qubit operations. Essential figures of merits include the operation speed, switching contrast, insertion loss and device footprint. Cryogenic compatibility is advantageous as well. Ultimately, the switching speed (switch repetition and on/off time) is faster than the radiative emission time of the quantum emitter (that is, sub-nanosecond), allowing control of each emitted photon. However, in many practical cases a much lower switching speed can be tolerated, since the photon source may not be operated at the highest possible internal repetition rate and/or the switching of blocks containing ten photon pulses (for example) will suffice. Indeed, switching blocks of photons decreases the count rate of a demultiplexed single-photon source only linearly, as opposed to the exponential scaling of loss. Usable switching rates range from tens of megahertz to several gigahertz is achievable, for example, with electro-optical devices[35] or nano-electro-mechanical devices[36]. These methods also allow the splitting ratio to be controlled, which facilitates the preparation of arbitrary photonic qubits.

The switching loss budget is essential and various material platforms feature low-loss waveguides, including silicon nitride (SiN)[37], silicon (Si)[38], and lithium niobate ($LiNbO_3$)[39]. Reducing the overall device footprint, which is determined by the refractive index contrast and applied switching method, is key for low-loss performance. Three $LiNbO_3$ electro-optical switches have been integrated and operated at 80 MHz for demultiplexing of a QD source into four modes[35], and the development of thin-film $LiNbO_3$ technology could lead to further improvements[40]. Combining different materials allows the electro-optic effects to be boosted, which could lead to smaller footprints[41].

Nano-opto-mechanical devices based on electrostatic or piezoelectric control offer novel opportunities[42] featuring small footprints and therefore ultra-low-loss performance. Furthermore, the capacitive nature of the actuation leads to low electrical noise. Switching speeds of 12 MHz have been achieved[43] and single photons from a QD were routed with only 15% insertion loss[36]. Furthermore, wafer-scale integration of $240\times240$ switching arrays have been realized[44], demonstrating the promising potential for scalability.

**Optical filters.** Optical control pulses are generally required to operate photon–emitter interfaces, and on-chip optical filters allow pump stray light (for example) to be rejected, or phonon sidebands to be removed. Reconfigurability is required to tune the filter to the QD resonance, and both tunable high-quality-factor ($Q$) cavities[45–47] and multi-layer gratings[48] have been implemented. Along with low insertion loss, ideal filters feature high extinction of stray light, tailored passbands, wide-band tuneability and operation at cryogenic temperatures. Spectral filtering of QD single-photon sources was realized using thermal and strain tuning[45,46] and nano-opto-mechanical tuning[47]. A quantitative benchmark is $Q\approx10^4$, which suffices for filtering of phonon sidebands.

**Optical delays.** Processing of photonic quantum information requires optical delay lines, which can be realized on-chip in low-loss optical waveguides or by routing photons into an optical fibre delay. Photon propagation does not introduce decoherence (apart from residual loss) and therefore a low-loss optical delay line controlled by an optical switch constitutes a practical quantum memory. Ultra-low-loss delay lines of up to 27 m in length (producing a 136 ns delay) have been realized in SiN featuring <0.1 dB m$^{-1}$ loss[37,49], which would allow interference of photons from deterministic chains of about 100 photons. Typical fibre losses are 3.5 dB km$^{-1}$ at the native QD operation wavelength (≈950 nm), and improve to 0.18 dB km$^{-1}$ at the telecom C-band.

**Frequency conversion.** With current growth and fabrication methods, solid-state quantum emitters have limited tuneability and emitter inhomogeneity is an issue. Nonlinear frequency conversion overcomes these challenges by translating the photon frequency, as controlled by a tunable pump laser and $\chi^{(2)}/\chi^{(3)}$ nonlinear materials. Conversion of a QD source to the C-band was reported in periodically poled $LiNbO_3$ crystals with an end-to-end efficiency of ≈35% (ref. [50]), which may be further improved by engineering the coupling to the nonlinear crystal, since the internal efficiency is near unity. Advances in thin-film $LiNbO_3$ (ref. [51]) and modal phase-matching of GaAs waveguides[52] hold promise for on-chip $\chi^{(2)}$ nonlinear conversion. Finally, the $\chi^{(3)}$ nonlinearity of integrated Si or SiN waveguides and cavities have been applied for frequency conversion of QD single-photon sources[53].

**Single-photon detectors.** To scale up quantum photonics, all components need to be low-loss and mutually compatible. This applies to the read-out of photonic quantum information as well. Recent decades have witnessed significant progress in single-photon detectors[31]. Key specifications of single-photon detectors include: low timing jitter, high-speed operation, near-unity efficiency, low dark count rates and (preferably) compatibility with PIC technology. SNSPDs have emerged as a promising technology that meets all of these requirements[54], reaching ≥98% detection efficiency[55], >1.5 GHz count rates[56], <10 dark counts per second[57] and <3 ps timing jitters[58]. Furthermore, photon-number-resolving detection can be realized using arrayed SNSPDs[59]. This progress renders SNSPDs a mature technology that can be implemented in the complex architectures considered here.

**Reconfigurable photonic circuits.** Advanced PICs are fabricated in mature commercial foundries and enable processing of large photonic resources. Quantum PICs typically comprise an array of input waveguides routing photonic qubits into a complex architecture of Mach–Zehnder interferometers. These circuits are reconfigurable, for example through thermo-optical transduction, but cryo-compatible tuning mechanisms have also been developed. PIC technology can be scaled up to a remarkable complexity. For example, a universal linear optics circuit was constructed using 26 input waveguides and 88 Mach–Zehnder interferometers[60], although so far probabilistic photon sources have been applied[61]. Rooted in this advanced technology, additional quantum photonics resources can be integrated, notably deterministic photonic sources and quantum nonlinearity (Fig. 3) to progress beyond the paradigm of linear quantum optics. To this end, the maturity of PICs is a major asset for photonics compared with other qubit technologies. With PIC technology, the ultimate scaling up to process thousands and millions of qubits may be envisioned, which is required for long-term applications of fault-tolerant quantum computing[7].

## Photonic quantum resources

By combining the deterministic photon–emitter interface with the variety of building blocks discussed above, a wide selection of high-fidelity quantum states can be prepared on demand, which corroborates the flexibility and scalability of the approach.

**Multi-photon sources.** A deterministic single-photon source can be demultiplexed to realize multi-photon sources. A demultiplexing architecture is illustrated in Fig. 4a: the deterministic train of photons is routed to different spatial modes by cascading switches, and the mutual delays of the photons are compensated by varying optical delays (such as fibres). The scalability is ultimately determined by residual switch and delay losses (Fig. 4b), while state-of-the-art QD sources deliver many high-quality qubits, as discussed previously. This highlights the general opportunity for QD sources where even a few matter qubits can produce many high-fidelity photonic qubits for subsequent demultiplexing and processing. So far, demultiplexing of up to 20 simultaneous photons from a QD has been experimentally realized using bulk optical components[62], and improved QD sources allow scaling into the quantum advantage regime (Box 1). Low-loss chip-integrated demultiplexing schemes could potentially scale up the multi-photon sources even further, as out-coupling loss can be avoided.

**Heralded entanglement sources.** Based on highly indistinguishable multi-photon sources, more advanced entanglement sources can be synthesized by quantum interference. Heralding can be incorporated at the cost of additional photons, whereby entanglement is generated on demand. Specific examples are two- and three-photon entanglement, exemplified by Bell and Greenberger–Horne–Zeilinger (GHZ) states. These are also essential building blocks for large multi-photon entangled states; indeed, three-photon GHZ states suffice for synthesizing a universal multi-photon cluster state

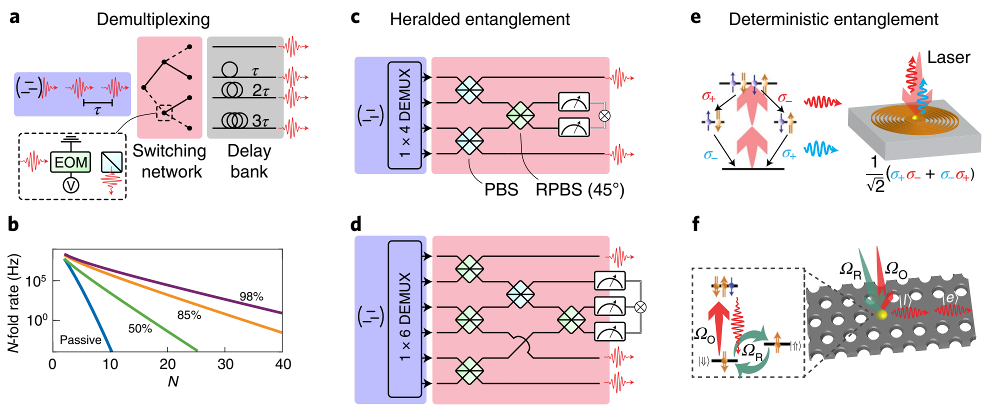



**Fig. 4 | Multi-photon and entangled photon generation. a**, Sketch of a demultiplexing (DEMUX) set-up that switches (using electro-optic modulators (EOM) and polarizing beam splitters (PBS)) subsequently emitted photons from a deterministic source into separate spatial modes with compensating optical delays to produce $N$ separate single-photon sources. Here $N = 4$ is illustrated. **b**, Rate of producing $N$ photons in an $N$-channel demultiplexing set-up for a deterministic single-photon source (source efficiency 78%, 1 GHz repetition rate) for various values of loss per switching event and including realistic fibre (delay lines for matching the EOM switching time of $4\tau$) and mode-matching losses (total efficiency of 90%; refs. [62,115]). **c**,**d**, Layout of photonic circuits for realizing polarization-encoded heralded entangled Bell (**c**) and three-photon GHZ (**d**) states, respectively. Here RPBS is a rotated polarizing beam splitter that separates diagonal and anti-diagonal polarized states. **e**, Level structure of a biexciton cascaded decay producing a polarization-entangled Bell state on demand and from the rotation symmetric photonic nanostructure. **f**, Protocol for the deterministic generation of a multi-photon cluster state by repeatedly exciting a QD that subsequently emits photons to the waveguide[75]. By implementing coherent spin rotations, entanglement is generated where the qubit is encoded in either an early (e) or a late (l) time bin. $\Omega_R$ and $\Omega_O$ are the Rabi frequencies of the rotation and optical excitation lasers, respectively. Panel **e** adapted with permission from ref. [17], Springer Nature Limited.

by ballistic scattering in a linear optics circuit[63]. Figure 4c and d illustrate the linear optics circuits required to produce heralded Bell and GHZ states starting from four and six photons, respectively[64,65]. The protocols have been realized with probabilistic sources[66] (that is, with limited efficiency) and heralded Bell-state generation was demonstrated with a deterministic QD source[67]. Unfortunately, the linear-optic approach introduces an unavoidable inherent loss; for instance, the Bell pair generation in Fig. 4b has a 3/16 probability of success. Nonetheless entanglement generation rates exceeding the megahertz scale are within reach with deterministic QD sources, which would be an important step forwards compared with the performance of probabilistic sources.

**Deterministic Bell sources.** An alternative route to Bell-state entanglement generation exploits a QD radiative cascade from a biexciton, which can be deterministic[16]. The source efficiency can be boosted with photonic nanostructures in which in-plane rotationally symmetric structures are required to retain the symmetry necessary for polarization entanglement. Figure 4e shows a bull's eye grating that has been successfully applied for Bell state generation[17] and an electrically driven entanglement source has been reported[68]. Biexciton entanglement sources have been applied for QKD[69] and enable hyper-entanglement generation (simultaneous entanglement in time and polarization)[70]. Hyper-entangled states could enhance the channel capacity in quantum communication protocols or enable deterministic entanglement purification[71].

**Deterministic multi-photon entanglement sources.** Introducing a spin to the QD provides further opportunities for entanglement generation. Coherent control of a spin can be used to entangle subsequently emitted photons: the quantum knitting machine[72]. A metastable spin ground state in a QD is prepared by tunnelling in a single carrier (either an electron or a hole) in electrically gated devices; the corresponding level system is depicted in Fig. 4f, in which an external magnetic field aligns the spin. Spin–photon entanglement has been demonstrated[73], which in combination with a repeated and alternating sequence of spin rotations and photon emissions, has led to the explicit demonstration of three-qubit entanglement[74]. How these encouraging results can be scaled up in future experiments has been an open question given the physical imperfections of the photon–emitter interfaces. To this end, it was predicted that for realistic physical parameters, QDs in nanophotonic waveguides may generate long (that is, more than ten) multi-photon cluster states with an infidelity per photon of only 1.6% (ref. [75]) in a particularly favourable time-bin encoding protocol (Fig. 4f). This fidelity reaches the demanding requirements for measurement-based fault-tolerant quantum computing. Time will tell whether such sources can break new ground for photonic quantum simulators and advanced quantum communication protocols, possibly even before reaching the fault-tolerance threshold.

**Higher-dimensional photonic cluster states.** For the most advanced quantum photonics applications, especially measurement-based quantum computing[76], photon entanglement along a one-dimensional string is not sufficient—two- or three-dimensional entangled clusters are needed. Such higher-dimensional cluster states can be synthesized by linear optics fusion gates[63], at the cost of reduced efficiency and a vast amount of ancillary photons. Deterministic sources can be realized by coherently coupling two quantum emitters hosting spins[77] or by routing back a one-dimensional entangled photon string in real time to the spin to create entanglement links beyond the nearest neighbour[78]. Coupled QDs can be produced via optical or tunnel coupling, as discussed previously. Furthermore, an all-optical spin–spin gate can be implemented with two QDs each in separate arm of an interferometer and sending a single photon through it. The observation of the photon in a certain output mode heralds the spin–spin gate[79]. This gate can achieve near-unity fidelity and success probability in the limit where the $\beta$ factor of the photon–emitter coupling approaches unity.

**Nonlinear quantum optics with photon–emitter interfaces.** The deterministic photon–emitter interface also realizes a giant photon nonlinearity leading to novel opportunities. An emitter can only scatter one photon at a time. If a narrow-band (relative to the emitter linewidth) photon interacts coherently with a high-$\beta$-factor emitter, the scattering probability approaches unity. Consequently, strong

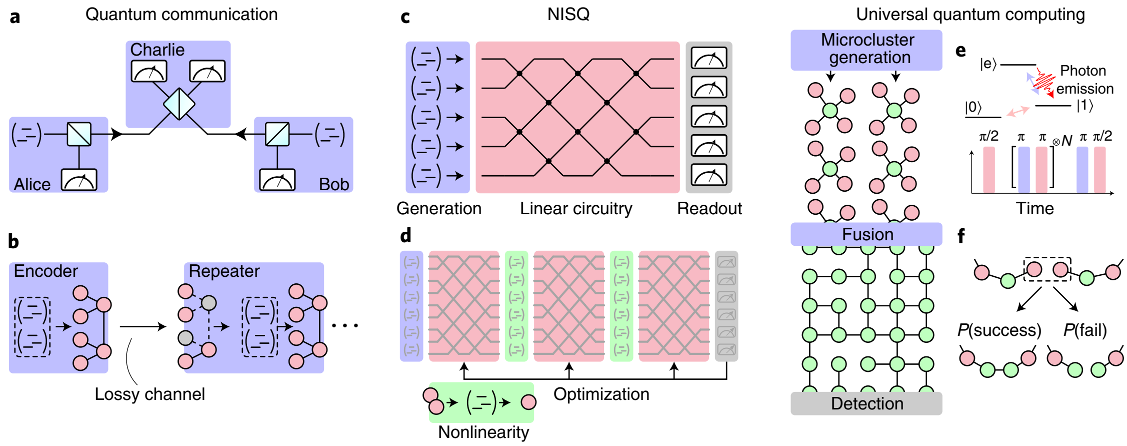



**Fig. 5 | Applications of deterministic photon–emitter interfaces in quantum communication and quantum computing. a**, Generic quantum cryptography protocol for sending encrypted keys with single photons. **b**, Operation principle of a one-way quantum repeater in which a qubit is encoded non-locally in a photonic cluster state, sent through a lossy channel and re-encoded at the next station. **c**, Generic layout of a reconfigurable PIC that is fed by QD sources to realize a NISQ device. **d**, Generic layout of a quantum photonics neural network composed of sources, reconfigurable linear PICs, nonlinear interaction layers and efficient detectors. **e**, Illustration of small-scale photonic cluster state generation with QD sources. **f**, Probabilistic fusion of small-scale cluster states into a percolated cluster state for quantum computing. Combining small-scale clusters (microclusters) through linear fusion gates followed by efficient detection is the template for building a universal quantum computer.

photon–photon correlations are introduced if the incident pulse contains two or more photons[80]. Introducing a spin allows a photonic switch controlled by a single emitter to be constructed[81] and if the spin state is coherently controlled, a Schrodinger cat state can be produced[82]. These nonlinear interactions constitute non-Gaussian photonic operations. Interestingly, non-Gaussian operations are the missing key functionalities in quantum information processing using continuous variables[83], as opposed to discrete qubit technology considered here. Hybrid discrete–continuous variable photonic quantum architectures remain an interesting future research direction.

## Applications

Among the plethora of quantum technology applications, we will focus on quantum cryptography and photonic quantum computing, which are well suited to deterministic photon–emitter interfaces.

Quantum cryptography exploits encoded quantum information to distribute encrypted messages. The protocol security is guaranteed by the laws of quantum mechanics[84]. A quantum key can be distributed using a stream of single-photon qubits over long distances and eavesdropping on the transmission channel can be detected (Fig. 5a). Deterministic single-photon sources will probably be of relevance in advanced QKD protocols offering ultimate security. Device-independent QKD is one such protocol and requires very efficient sources of highly indistinguishable photons for entanglement generation. The observation of a Bell-inequality violation testifies system protection against side-channel attacks on the receiver/sender hardware as well[85]. High-quality deterministic single-photon sources have been proposed for a fully device-independent and heralded QKD implementation[86], for which the challenging requirements in terms of source efficiency and photon indistinguishability seem reachable with QD sources integrated with small-scale circuits and detectors. Another related application is the generation of true random numbers with important applications in computing and fundamental tests of quantum physics[87]. Quantum random number generators can be made device-independent[88] in a similar manner to the QKD protocol.

Multi-photon entanglement sources lead to more opportunities. One general idea is to encode a qubit of information non-locally in a multi-photon entangled cluster, as opposed to using a single photon. Such multi-photon encoding makes the qubit more robust towards loss and errors. The most essential component for quantum communication is the quantum repeater[89], which allows the distribution of quantum information over extended distances in the presence of unavoidable optical loss. Ultimately, a quantum repeater is key for scaling up distributed quantum computing to construct a quantum internet[90,91]. A long-lived quantum memory efficiently interfaced with the photonic links for photon storage underpins repeater architectures; however, this is a challenging (yet maturing) research direction[92]. An alternative architecture is termed the one-way quantum repeater[93]; it circumvents the requirement for a long-lived quantum memory and is therefore well suited to QD-based photonic hardware. Here the qubit is encoded non-locally in a cluster state at a transmitter station and entanglement distribution proceeds by directly transmitting the cluster state. The redundancy of encoding in multiple photons implies that the qubit is loss tolerant and can therefore be re-encoded in a new photon cluster at the receiver station for further transmission (Fig. 5b). Coupled QDs can be configured to generate photonic cluster states suitable for quantum repeaters[94] and, based on that, a blueprint of a QD-based one-way quantum-repeater protocol was formulated and benchmarked[95]. This protocol is tailored to QD hardware such that only three QDs per repeater station are required, and was found to be realizable with experimentally feasible values of photon–emitter coupling, spin coherence and spin–photon gate fidelity.

Full-blown quantum computing is possible using only single photons and linear optics[96]. However, the resource requirements are staggering and additional hardware is required to make this approach feasible. This Review introduces such opportunities using the nonlinear photon–emitter interface. It is interesting to consider whether specialized photonic quantum simulators could be developed for specific computing tasks within the current era of noisy intermediate-scale quantum (NISQ) processors[97]. Measurement-based quantum computing protocols[76] are well suited to photonics where a multi-photon entangled state is generated up front and subsequent single-qubit measurements implement the algorithm. A promising direction would be to tailor a multi-photon cluster state to a specific application, or with a specific loss tolerance target[94], which could be significantly more resource-efficient than starting with a universal cluster state that contains many redundant qubits.

Quantum photonics is well suited to simulating the dynamical evolution of complex quantum systems. Photons propagating through PICs emulate the physical system and the propagation depth of the PIC represents the evolved time (Fig. 5c). Photonics could probably offer quantum advantage in the near future using current NISQ technology. So far, proof-of-concept quantum simulations of molecular vibrational dynamics have been carried out with probabilistic sources[98]. Such simulations can be scaled up with deterministic photon sources, and anharmonic vibrational effects can be considered, which require nonlinear interactions. Another emerging application area concerns the simulation of molecular dynamics problems, such as the dissociation of molecular bonds resulting from molecule–molecule interactions or the docking of a small molecule onto a larger host[99]. Despite being inherently quantum, such processes are today simulated by approximate molecular dynamics methods that rely on solving Newtonian equations of motion[100]. A photonic quantum simulator could be configured to treat such problems fully quantum mechanically, thereby testing the validity of existing methods. Precise simulations of vibrational dynamics and molecular docking are required for modelling complex protein folding problems. A hybrid quantum–classical processor could be advantageous, in which a designated part of the problem is solved quantum mechanically while the rest is approximated by classical means. Computation of protein folding problems is a major challenge in drug discovery, and even modest computational advantages could be of major value and impact[101].

Variational quantum algorithms constitute another class of algorithm well suited to photonics due to the availability of flexible and reconfigurable PIC hardware. These algorithms require coherent quantum evolution of a very limited depth together with a classical algorithm that subsequently updates the quantum circuit before next iteration. The limited resource requirement has driven proof-of-concept photonics implementations for determining molecular ground-state energies[102]. Quantum neural networks[103] offer another opportunity conveniently using the reconfigurable PIC platform. The overall idea is to exploit the massive amount of information contained in large-scale quantum states as a novel resource for training algorithms. Quantum neural networks require nonlinearity and could be implemented in photonics via deterministic photon–emitter interfaces; see Fig. 5d for an illustration of a quantum photonics neural network[104]. Such a processor could be trained, for example, to synthesize a desired multi-photon entangled state for targeted measurement-based quantum algorithms.

Large-scale fault-tolerant quantum computing is the ultimate challenge for any quantum computing technology. It has been argued that PIC technology is a major raison d'être for photonic quantum computing, suggesting a realistic technological pathway to meeting the daunting requirements for fault tolerance[7]. Measurement-based quantum computing architectures[105,106] currently seem to be the most promising approach. It remains to be seen whether the metrics of the photonic qubits can be of sufficient quality to reach fault tolerance. In this Review, we have covered two approaches to achieve the percolated large-scale photonic cluster states required for quantum computation: (1) on-demand generation by coupled QDs and (2) fusion of three-photon GHZ states. The advantage of (1) is that the cluster state is produced deterministically, but is susceptible to imperfections of the QD source. Whereas for (2), percolation of the cluster is done by linear optics, which does not introduce decoherence but relies on probabilistic photon fusion and requires ancillary photons to boost the efficiency[63]. An optimum strategy is probably a combination of the two, in which the QD sources are used to generate small-scale clusters on-demand and linear fusion subsequently grows the state (Fig. 5e,f). Another opportunity would be to exploit the nonlinear photon–photon interaction mediated by QDs to improve the photon fusion operation beyond the limitations set by linear optics. An explicit protocol for a Bell-state analyser has been put forwards based on deterministic photon–emitter interfaces[107].

## The road ahead

Deterministic and coherent photon–emitter interfaces are now routinely realized in scalable solid-state devices. We have summarized some of the near- and long-term applications that this novel photonic building block could enable. Compatibility with a host of other photonic functionalities is essential, and we have highlighted the requirements and relevant specifications. Looking ahead, it is obvious that very serious engineering efforts are required to take the next step in this burgeoning area of technology and tackle real-world problems. Indeed, in many cases the fundamental principles have been demonstrated for each device/functionality separately, but merging the building blocks in advanced applications sets strict requirements on fabrication yield and reproducibility, coupling loss and cross-talk between devices. Excitingly, the high performance and thorough fundamental understanding of the building blocks now justify serious technology development, and we will probably see further quantum photonic hardware development gradually shifting towards industrial labs.

While the all-solid-state QD platform has a number of appealing features, two main issues require more attention: (1) reducing emitter–emitter inhomogeneity and (2) coupling to a long-lived quantum memory. Although the protocols discussed here have been tailored to sidestep these limitations of QDs, it is also clear that overcoming these obstacles would lead to an even more powerful and capable platform. The former challenge pertains primarily to QD growth, and could be resolved if QDs were reproducibly synthesized with atomic precision at predetermined positions. The latter requires additional degrees of freedom for storage, and one promising approach exploits coupling to the QD nuclear spins[108]. Alternatively, a hybrid approach may be pursued, where QDs are coupled to ensembles of atoms or ions[109,110] or ultra-long-lived opto-mechanical oscillators[111], for example. In these cases, efficient bandwidth and wavelength matching of the two systems is required, which could be pursued with nonlinear conversion.

Hybrid interfacing with photonics may enable even more opportunities. In many-qubit systems, for example based on spins or superconductors, qubit–qubit interactions beyond nearest neighbour are usually weak, which limits their scalability. An efficient quantum interface with photons would allow long-range interactions to be established. Photonic links have also been proposed for scaling up ion–trap quantum computers[112]. Such interfaces require proper quantum coherent transduction between the different qubit operation frequencies, such as transduction from microwave to optical frequencies in the case of superconductor–photon coupling[113]. A QD photon–emitter interface could be configured to implement transduction, for example by driving a tailored Raman transition in coherently coupled QDs[114]. Such a hybrid interface could lead to entirely new opportunities using matter degrees of freedom for computation and photons as communication links. The availability of the coherent and deterministic photon–emitter interface today, the point of departure of this Review, implies that such advanced hybrid interfaces are within reach. The ultimate dream of a large-scale quantum internet or a scaled-up quantum computer could be the outcome of such advancements.

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## Competing interests
P.L. is founder of the start-up company Sparrow Quantum.

## Additional information
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